Modeling vegetation fires and fire emissions

Book Section

14 Modeling Vegetation Fires and Fire Emissions

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Abstract

Fire is the most important ecological and forest disturbance agent worldwide, is a major way by which carbon is transferred from the land to the atmosphere, and is globally a significant source of greenhouse gases and aerosols. Wildfires across all major biome types globally consume about 5% of net annual terrestrial primary production per annum, and release about 2-4 Pg C per annum, of which approximately 0.6 Pg C comes from tropical deforestation and below-ground peat fires. The global figure is equivalent to about 20-30% of global emissions from fossil fuels. Tropical savannas comprise the largest areas burned and greatest emissions sources from vegetation wildfires. Fires in Mediterranean forests and shrublands, tropical forests and boreal forests are also significant sources of emissions because they are generally characterised by much higher fuel loads per unit area compared with grasslands. Improved satellite data and sophisticated biogeochemical modeling enables emissions assessments on a global scale with fine spatial and temporal resolution. Emissions estimates are still comparable to those based on older inventory-based techniques, but uncertainties remain large. Fires increase during El Niño periods because parts of the tropics where humans use fire as a tool for deforestation experience drought conditions. These spikes contribute to the inter-annual variability of CO_2 and CH_4 observed in the atmosphere. Recently developed dynamic fire-vegetation models are capable of simulating the extent of wildfires as well as their emissions of CO_2 and other greenhouse gases for ambient as well as for projected climatic conditions. The performance of fire-vegetation models however needs to be strongly improved and validated.

Keywords: Modeling vegetation fires, dynamic fire-vegetation models, prognostic fire models, carbon equivalent, emission factors

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Published in: Vegetation Fires and Global Change – Challenges for Concerted International Action
A White Paper directed to the United Nations and International Organizations (Johann Georg Goldammer, ed.)
A publication of the Global Fire Monitoring Center (GFMC)

Why is Fire an Important Process in the Earth System?

Fire is the most important disturbance agent worldwide in terms of area and variety of biomes affected, a major mechanism by which carbon is transferred from the land to the atmosphere, and a globally significant source of aerosols and many trace gas species (Bowman et al., 2009). Wildfires operate on all continents apart from Antarctica, globally consuming on average perhaps 5% of net annual terrestrial primary production (Randerson et al., 2005), and taking into account below ground peat fires, are estimated, on average, to emit an amount of carbon equivalent to 2 Pg C per annum (van der Werf et al., 2010). This is equivalent to about 20% of global emissions from fossil fuels (Denman et al., 2007). Wildfires are estimated to burn 200-500 million hectares worldwide each year (Lavorel et al., 2007), with burning characterized by a diurnal cycle, generally strong seasonality, and potentially very large inter-annual variability at the regional scale (Giglio et al., 2010). Savannas are, on average, the single largest area burned and greatest emissions source (van der Werf et al., 2010). However, Mediterranean forests and shrublands (Moreno, 1998), tropical forests (Page et al., 2002; Cochrane, 2003) and boreal forests (Balzter et al., 2005), where fuel loads per unit area and thus emissions are typically much greater than in grasslands, are also significant in the global context (Figure 14.1).

Fire disturbance has a major impact on vegetation dynamics by initiating succession, selecting fire-adapted plants in fire-dominated ecosystems and influencing vegetation productivity, and thus litter and fuel load (Whelan, 1995; Goldammer and Furyaev, 1996; Cochrane, 2003; Bergeron et al., 2004). Burning conditions are driven by climate and vegetation state. Fire effects include post-fire mortality of plants and depend on the regeneration mode of the vegetation and fuel composition; these in turn define the burning conditions for the next fire event. Fuel load in ecosystems of highly variable productivity can demonstrably limit or promote fire spread (Mermoz et al., 2005; Spessa et al., 2005; Stephens and Moghaddas, 2005), whereas temperature is the main limiting factor in fire season duration in boreal and temperate ecosystems (where fuel availability is generally high) (Schimmel and Granström, 1997; Flannigan et al., 2005). The inter-annual variability in area burned, fuel consumed and emissions released in parts of the boreal and tropical regions can be as large as a factor of two orders of magnitude, driven principally by climate-related variations in fuel loads, fire susceptibility (e.g. fuel moisture), fire severity and fire duration (French et al., 2002; Sukhinin et al., 2004; Flannigan et al., 2005; Randerson et al., 2005; Kasischke et al., 2005; van der Werf et al., 2006, 2010). Fire is not only an important process shaping ecosystem structure and function on contemporary time-scales, but also on longer time-scales in the past (Feurdean et al., 2012; Pfeiffer et al., 2013).

Fire is a key component of the carbon cycle. Globally, annual pyrogenic C emissions in the last decade are calculated to have peaked in the ENSO year of 1998 (2.8 Pg C yr^{-1}), with a minimum in 2009 (1.5 Pg C yr^{-1}) (van der Werf et al., 2010). Furthermore, above ground wildfires emit on average about 1.5 Pg C yr^{-1} to the atmosphere, with the majority stemming from savanna fires in Africa (50%) and smaller but significant contributions from fires in the tropics, Mediterranean regions, and the boreal zone (van der Werf et al., 2010). From

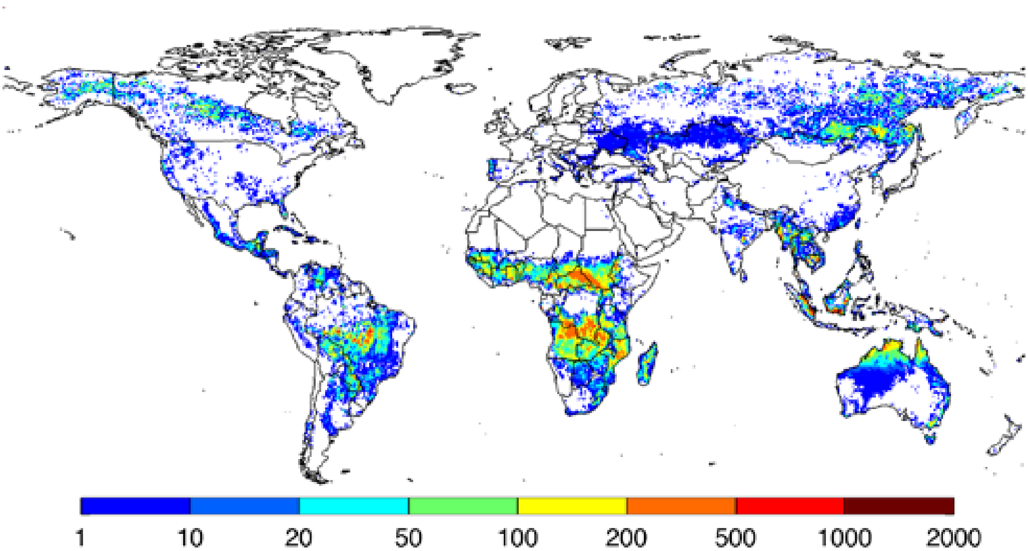

Figure 14.1. Average carbon losses from above and below ground wildfires, 1997-2009 (gC per square metre per annum). Source: van der Werf et al. (2010) Global Fire and Emissions Database (GFEDv3) (http://www.falw.vu/~gwerf/GFED/index.html)

a CO_2 perspective, emissions of these fires are believed to be balanced over decadal scales by carbon uptake from regenerating vegetation. However, this is certainly not the case for the large range of other trace gases as well as aerosols released by fires (Andreae and Merlet, 2001). Nor does it apply to CO_2 released from deforestation and peatland fires, which occur mostly in South America and Southeast Asia. Although uncertain in terms of methods used to estimate burnt area and carbon combusted, these fires emit, on average, about 0.6 Pg C yr^{-1} (van der Werf et al., 2010) and therefore, contribute significantly to the build-up of atmospheric CO_2.

As the review by Andreae (this volume, Chapter 13) highlights, over the past ten years, several studies have provided global estimate emissions from biomass burning, and while differences between studies exist, these differences can generally be accounted for by the data and methods used. For example, annual average global emissions from biomass burning presented in GFEDv3 (van der Werf et al., 2010) are lower than those presented by Andreae (this volume, Chapter 13) at about 4.3 Pg C yr^{-1} because the latter includes biofuel use, at about 1.7 Pg C yr^{-1}, and is based on different data sources, principally older and coarser-scale satellite data. Furthermore, GFEDv3 total estimates are slightly lower than those of the more recent work by Kaiser et al. (2012) who used a different technique for estimating global emissions from wildfires. Kaiser et al. (2012) used daily estimates of Fire Radiative Power (FRP) (Roberts et al., 2005; Wooster et al., 2005) to derive biomass burnt and emissions from wildfires, and calculated a slightly higher estimate from wildfires globally compared with van der Werf et al. (2010) (Kaiser et al.: 2.1 Pg C yr^{-1}; van der Werf et al.: 2.0 PgC yr^{-1}). Regardless of which satellite product is used, it is widely acknowledged that uncertainties associated with cloud cover and overpass timing remain, and as such, further work is underway to reconcile global estimates from biomass burning using satellite and model-based inversion techniques, for example, between the CO measuring space-borne MOPITT (Measurements Of Pollution In The Troposphere) instrument and GFEDv3 (van der Werf, pers. comm.).

Some suggest fire to be the largest source of inter-annual variability in land-atmosphere C fluxes, with an estimated inter-annual variability of approximately 1 Pg C (1997 to 2004) (Patra et al., 2005). Biomass burning contributes up to 50% of global CO and NOx emissions in the troposphere (Galanter et al., 2000) and may be responsible for significant increases in atmospheric growth rates of CO, CO_2 and CH_4 during ENSO events (van der Werf et al., 2004). Simpson et al. (2006) confirmed the influence of biomass burning on large global CH_4 pulses in 1998 and 2002-2003, and that growth rate fluctuations in methane reflect the influence of ENSO activity on large-scale biomass burning in the tropics. However, some contend that there are additional uncertainties on these amounts that are of similar magnitude to the interpreted variability due primarily to uncertainties in the estimates of global area burnt, fuel load and burning conditions under specific fire regimes (French et al., 2004; van der Werf et al., 2006, 2010).

In addition to its impact on global greenhouse gas levels, fire also modifies a variety of land-atmosphere interactions at different spatio-temporal scales (e.g. vegetation transpiration, surface roughness soil erosion, albedo). Forest fires, deforestation and other forest disturbances effectively thin forests, reducing the amount of vegetation transpiring water. In the Amazon, for example, reduced overall transpiration through forest loss results in lowered local atmospheric humidity levels, and increases the probability of future forest fire occurrence (Cochrane, 2003). At the regional scale, transpiration from Amazonian forests is important for downwind precipitation, contributing over 25% to annual rainfall (Cochrane, 2003). Forest fires reduce the ability of affected forests to retain water, exacerbating flooding, erosion and seasonal water shortages. Smoke-borne aerosols from fires disrupt normal hydrological processes and reduce rainfall, potentially contributing to regional drought (Andreae, 2007). Wildfires thus have the ability to significantly perturb Earths radiation budget and climate, with the possibility for positive feedback (Denman et al., 2007).

Regional- and Global-Scale Fire and Emissions Quantification

The effect of fire on climate and atmospheric chemistry is known to be crucial. However, until recently, estimates of wildfire emissions of trace gas and aerosols to the atmosphere have been based almost solely on so-called 'bottom-up' inventories or emission models (Hoelzemann et al., 2004; Kasischke et al., 2005) which use the equation of Seiler and Crutzen (1980)

$$C_t = A \times B \times FC \times CE \qquad (1)$$

where total carbon emission C_t is the product of the area burnt A (ha), the average density of biomass B (tons per ha), the carbon fraction of the biomass FC and a scaling factor (CE for combustion efficiency (fraction of available fuel that actually burns). Emission factors for trace gas and aerosol species (e.g., Andreae and Merlet, 2001) can be used to estimate the release of any other species from the estimates of C_t produced from (1). Early attempts to estimate emissions were based on biome-scale assessments of the input variables (Seiler and Crutzen, 1980).

More recently, satellite data has been used to assess area burned (e.g. Roy et al., 2003, 2008, 2009; Giglio et al., 2010; Tansey et al., 2008) and drive biogeochemical models (e.g. CASA, Randerson et al., 1996) and vegetation dynamics models (e.g. LPJ-GUESS, Smith et al., 2001) to better estimate the spatio-temporal variability in biomass burning and emissions (e.g. van der Werf et al., 2010; Ito and Penner, 2004; Lehsten et al., 2008; Schultz et al., 2008). However, all previous studies have used static emission factors to calculate emissions from wildfires. This neglects the reality that emissions of trace gases and aerosols critically depend on the moisture conditions of the combusted fuel. With wet fuel generating resulting in incomplete combustion and higher ratio of non-CO_2 n-greenhouse gases compared to dry fuel. One attempt to take this into account is to quantify the amount of burned wood versus the amount of burned litter and use this ratio to generate dynamic emission factors (Scholes et al., 1996). In addition, variability in CE and emission factors (e.g. Shea et al., 1996; Kasischke et al., 2005; Korontzi, 2005) can to some extent be simulated based on meteorological conditions and fuel composition.

Satellite-based estimates of fire activity have been highly useful to better understand the role of fire in the carbon cycle, better understand atmospheric processes and trace gas budgets, and quantify changes in air quality impacting people's health. Nonetheless, estimation approaches based solely on remotely sensed burned area measures can only be used for estimating emissions during recent decades at regional-scales; and generally much less continentally or globally since reliable Earth Observation (EO) data at these scales has only now become available for the past decade or so. Moreover, they cannot be used to predict climate-related changes in fire activity and pyrogenic emissions either in the longer-term past, or the future, for example, the next dry season or over decadal timescales.

It is therefore important to have access to validated models that allow one to make predictions outside of the contemporary satellite record. Prognostic fire models, embedded in dynamic global vegetation models (DGVMs), can in principle simulate the effects of changes in climate and vegetation dynamics as a bi-directional feedback with the embedded fire model. This capability is needed in order to investigate how fire and fire-related emissions might change with changing climate conditions and vegetation dynamics and to allow quantification of fire 'risk' based on emerging capabilities for seasonal meteorological forecasting.

Future Climate Change

Fire frequency and intensity are strongly sensitive to climate change and variability, and to land use practices (Denman et al., 2007). Over the last century, trends in burned area have been largely driven by land-use practices, through fire suppression policies in mid-latitude temperate regions and increased use of fire to clear forest in tropical regions (Mouillot and Field, 2005; Schultz et al., 2008). However, there is also evidence that climate change has contributed to an increase in fire frequency in Canada (Gillett et al., 2004) and fire severity in Central Asia (Goldammer, 2006). Several studies using outputs from GCMs to drive calculations of empirical fire danger indexes indicate that fire frequency will increase under the likely scenario of a warmer and/or drier future climate in many carbon-rich forests, including circumpolar boreal forests (Flannigan et al., 2009) and Amazonia (Cardosa et al., 2003; Golding and Betts, 2005).

Future prediction of both burnt area and emissions from wildfires under climate change requires more than just the calculation of fire danger, but rather a process-based understanding of the three main pre-cursors to fire viz. an ignition source, ample fuel, and suitably dry fuel (Pyne et al., 1996). Prognostic fire models, embedded in process-based vegetation models, can in principle simulate the effects of changes in climate and vegetation dynamics on fire activity and emissions. This capability is fundamental in order to investigate how fire and fire-related emissions might change with changing climate conditions, vegetation and land use patterns in future. Similar work cannot be achieved by relying on empirical fire danger indexes because they tell us only about the risk of fire.

Existing Models of Fire-Vegetation Interactions

There have been a number of previous attempts to simulate fire within dynamic global vegetation models (DGVMs) in order to simulate and study climate-fire-vegetation interactions (Lenihan and Neilson, 1998; Thonicke et al., 2001; Venevsky et al., 2002; Arora and Boer, 2006; Scheiter and Higgins, 2009; Kloster et al., 2010, Thonicke et al., 2010). Such models are designed primarily to incorporate the role of fire as a disturbance factor for vegetation dynamics, and to account for corresponding fluxes in the global C cycle (e.g. last glacial maximum, Thonicke et al., 2005). Trace gas and aerosol emissions can also be derived within these models via the aforementioned emissions factors.

Existing fire models display a wide variety of complexity in terms of how well they capture and/or abstract key fire-related processes. The Glob-FIRM model (Thonicke et al., 2001) in the LPJ Dynamic Global Vegetation Model (DGVM) (Sitch et al., 2003) predicts the fractional area burnt within a grid cell from the simulated length of fire season and minimal fuel load. However, it does not specify ignition sources explicitly and assumes a constant relationship between fire intensity and fire severity to describe fire effects. Fire resistance, a composite parameter to describe average fire intensity and fire severity, is defined as a parameter for each plant functional type (PFT) in the LPJ-DGVM. Reg-FIRM (Venevsky et al., 2002), an alternative regional-scale fire model in LPJ, treats climatic fire danger, wildfire ignitions and fire spread as distinct processes, but fire effects on vegetation mortality are prescribed parameters as in Glob-FIRM, and trace gas and aerosol emissions are not quantified. MC-FIRE, embedded in the MC1 DGVM, explicitly simulates fire spread (following Cohen and Deeming, 1985) and fire effects including post-fire mortality (Peterson and Ryan, 1986). However, it allows only one ignition per year per grid cell, and requires a drought index and information on time since last fire to estimate the fraction of the grid cell burnt (Lenihan and Neilson, 1998). Arora and Boer (2006) present a global simulation of fire activity and emissions from biomass burning within the Canadian Terrestrial Ecosystem Model (CTEM) (Verseghy et al., 1993); and Kloster et al. (2010) conducted a similar study having implemented CTEM-fire into the Community Land Surface Model (CLM) (Oleson et al., 2010). However, while CTEM-fire simulates the feedback between vegetation and fires, it adopts a simplified parameterized approach. Notably, it models fire rate of spread as a function of wind speed and soil moisture only, which ignores the influence of litter load and litter moisture. Also, fire-induced consumption of biomass and plant mortality are prescribed, and do not vary with changes in fire intensity. Scheiter and Higgins (2009) described a new vegetation model that was specifically developed for tropical vegetation. The model combines established components from existing DGVMs with novel process-based and adaptive modules for phenology, carbon allocation and fire within an individual-based framework. The fire model is semi-empirical, and for fire to spread, two conditions must be fulfilled: there must be an ignition source and the potential fire intensity must exceed a certain threshold. Potential number are limited by relative humidity only, and do not take into account socio-economic or demographic factors.

The fire model SPITFIRE (SPread and InTensity of FIRE) was designed to i) overcome many of the limitations in previous fire models set within DGVM frameworks, and ii) be flexible enough to permit simulation analyses at global scales as well as for any region, with minimal setup requirements (Thonicke et al., 2010). SPITFIRE was originally developed as an embedded module within the LPJ DGVM framework and is a successor to the RegFIRM fire model (Venevsky et al., 2002). RegFIRM explicitly simulates processes of climatic fire danger and wildfire lightning- and human-caused ignitions. SPITFIRE builds on this treatment with a more complete representation of ignitions and fire spread (if conditions are sufficiently dry) and comprises new process-based simulations of fire intensity and the risk of fire-damaged trees dying from either crown scorch or cambial death (the two most important causes of post-fire mortality), as well as emissions of trace greenhouse gases and aerosols from biomass burning.

SPITFIRE has been applied in coupled mode with the LPJ DGVM at global scales (Thonicke et al., 2010, Pfeiffer et al., 2013; Gomez-Dans et al., in review) and regional scales. Thonicke et al. (2010) focused on broad EO-based assessments of simulated burned area and emissions from biomass burning. Pfeiffer et al. (2013) did the same but from the perspective of developing improved fire modelling for pre-industrial applications. Gomez-Dans et al. (in review) used a combination of parameter calibration/optimization techniques, MODIS burned area data, and MODIS tree cover data to improve LPJ-SPITFIRE predictions of burned area at selected sites in different biomes. SPITFIRE has also been driven with L3JRC burned area data (Tansey et al., 2008) and MODIS burned area data (Roy et al., 2008; Roy and Boschetti, 2009) as part of the LPJ-GUESS vegetation model (Smith et al., 2001; Hickler et al., 2006) in a study examining emissions from biomass burning in Africa (Lehsten et al., 2008). Using LPJ-GUESS-SPITFIRE, Lehsten et al. (in review) examined how changes to fire frequency, including no fire, affects tree-grass ratios in Africa. Recently, Spessa et al. (2013) benchmarked LPJ-GUESS-SPITFIRE driven by a combination of monthly Global Fire and Emissions Database (GFEDv3) burnt area data (1997-2009) (Giglio et al., 2010; van der Werf et al., 2010) and long-term annual fire statistics (1901 to 2000) (Mouillot and Field, 2005) against EO-based tree biomass data for pan-tropical forests and savannas (Saatchi et al., 2011, Baccini et al., 2012). Finally, Spessa and Fisher (2010) completed the coupling of SPITFIRE to a global version of the Ecosystem Demography (ED) vegetation model (Moorecroft et al., 2001). ED has been run at global scale by Fisher et al. (2010) as part of the land surface model 'MOSES2.2' (Met Office Surface Exchange scheme) (Essery et al., 2001), and as part of the Community Land Surface Model (CLM) (Oleson et al., 2010). SPITFIRE is being implemented into the ED-CLM model (Spessa and Fisher, in progress).

LPJ-SPITFIRE simulates the number of fires, area burnt, fire intensity, crown fires, fire-induced plant mortality, and emissions of carbon, CO_2, CO, CH_4, VOC, NO_x, $PM_{2.5}$ and TPM at a daily, 0.5 degree resolution (Thonicke et al., 2010). In the model, the number of human-caused fires is modeled as a log-normal shaped function of population density, with the height of the curve dependent on the number of fires per capita per fire-season day. This parameter is empirically-derived from observed data on fires, the population density and the average fire danger conditions within a grid cell. The number of lightning-caused fires is currently prescribed and is sourced from flash rate data taken by the Optical Transient Detector (OTD) (Christian et al., 2003). Fire rate of spread (ROS) calculations are based on the USDA operational fire prediction models (Rothermel, 1972; Wilson, 1982), and are directly proportional to energy produced by ignited fuel, and also wind speed. ROS is inversely proportional to the amount of energy required to ignite fuels (fuel moisture and fuel bulk density, derived from the LPJ). Four dead fuel classes are considered in SPITFIRE: 1hr (dead leaves), 10hr (twigs/small branches), 100 (large branches) and 1000-hr (logs) classes. These values refer to the average time it takes for a fuel type to respond to equilibrium moisture conditions, which varies according to the surface area to volume (SAV) ratio of the fuel (e.g. leaves have high SAV and logs have very low SAV; Pyne et al., 1996). Area burnt is a function of ROS, and fire duration, assuming an elliptical shaped fire and the Canadian method for scaling the wind-directed long axis of a burn ellipse to the short axis (van Wagner and Pickett, 1985; CFFBG 1992). Litter moisture is simulated as a function of the fire 'danger' index, which in its current form is the Nesterov Index (Nesterov, 1949; Venevsky et al., 2002). Grass phenology (green-up and curing phases of annual grasses) is modeled as function of the upper soil moisture. Fuel combustion (by fine and coarse fuel classes) is simulated as a function of fuel moisture, while fire intensity is a function of both the calorific content of the fuels, the amount of fuel consumed and the fire ROS; and follows Byram (1959). Tree mortality and crown fires are modeled as a function of fire intensity, degree of cambial kill (which depends on fire residence time), and vegetation-specific attributes). Emissions are calculated using the Seiler and Crutzen equation (Equation1), with the emission factors of Andreae and Merlet (2001) and regular updates from the Max Planck Institute for Chemistry, Mainz.

Compared to the LPJ-DGVM, LPJ-GUESS and ED both represent a 'size and age structured' approximation of an individual based gap model (GUESS: Smith et al., 2001, 2011; Hickler et al., 2006, 2008; ED: Fisher et al., 2010). The major innovation of the LPJ-GUESS-SPITFIRE and ED-SPITFIRE models is the categorization of each climatic grid cell into a series of non-spatially contiguous patches. The patches can be thought of as analogous to different stages of the succession process, for example, after fire. Recently burnt patches in both LPJ-GUESS and ED tend to be dominated by shade intolerant vegetation, typically grasses; whereas less recently or undisturbed patches are generally dominated by shade-tolerant trees. These patterns reflect ecological reality. The age-class structure in LPJ-GUESS and ED further facilitates a more ecologically realistic representation of fire-induced mortality and light competition. By contrast, LPJ DGVM adopts an 'area-based approach' that implicitly averages individual and patch differences across 'populations' of vegetation types, and the climatic gridcell. As such, LPJ-DGVM cannot easily be used to simulate disturbance-based ecological succession.

Model Evaluation and Improvement using Earth Observation Data

For large-scale DGVM-fire models such as LPJ-SPITFIRE and ED-SPITFIRE, Earth Observation (EO) data, complimented by appropriate ground-based measures, are fundamentally important for model evaluation over the full range of eco-regions and climate regimes. LPJ-SPITFIRE has been validated at 0.5 degrees resolution against the GBS 1982 to 2000 burnt area series (available at 8 sq km resolution, Carmona-Moreno et al., 2005) (Thonicke et al., 2010). Comparisons with the satellite-derived Global Burnt Surface product (GBS, Carmona-Moreno et al., 2005) show that LPJ-SPITFIRE realistically detects area burnt over most of the globe (Fig. 14.2). However, the GBS product itself is known to underestimate burnt area in the boreal zone, and comparisons with a region-specific EO burnt area dataset indicate that LPJ-SPITFIRE actually produces a reasonable simulation of boreal fires recorded by Suhkinin et al. (2004) (Thonicke et al., 2010). Simulated biomass burning of actual vegetation, rather than potential, natural vegetation is, on average, about 2 Pg C per annum, which is compatible with estimates based on global inventories (e.g. van der Werf et al., 2010). LPJ-SPITFIRE has also been tested in selected regions using EO data on burnt area in southern Africa (Gomez-Dans et al., 2009), northern Australia, Borneo, western USA and Russia (Spessa et al., 2008) and Amazonia (Thonicke et al., 2009).

EO data are not only invaluable for testing model outputs (e.g. numbers of fires, and area burnt), but the increased sophistication of EO products in terms of the variables measured,

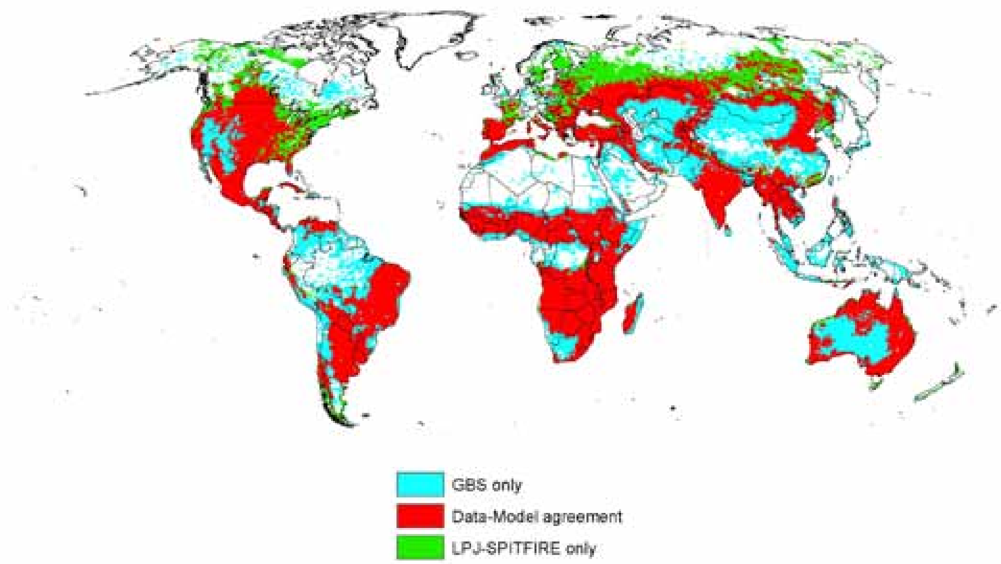

Figure 14.2. Comparison of simulated and observed area burnt based on a standard global LPJ-SPITFIRE simulation (Thonicke et al., 2010) and the GBS burnt area product covering 1982-99 (Carmona-Moreno et al., 2005). Data-model agreement (red): GBS detects fire and LPJ-SPITFIRE simulates area burnt greater than zero; area burnt detected by GBS only, but not LPJ-SPITFIRE (blue); area burnt simulated by LPJ-SPITFIRE only (green).

accuracy, temporal resolution and duration now enable the testing of individual components of the fire model, such as the simulation of fire rate of spread and fire intensity, in ways not possible only relatively few years ago (e.g. Dasgupta et al., 2006, 2007). Furthermore, many climate-related driving variables now have EO based analogues (e.g. land surface temperature, fuel moisture indices) that may assist greatly in the calculation of fire danger indices that currently rely on rather course scale interpolations of standard meteorological products or climate model outputs (Hao and Qu, 2007).

Wildland fires result in a wide variety of characteristic spectral signature changes that can be detected by remote sensing, including those related to the intense thermal emission from combustion (Lentile et al., 2006; Ichoku et al., 2003), to the albedo and spectral reflectance changes induced by burning, and to the presence of trace gas and aerosols smoke plumes (Jost et al., 2003; Trentmann et al., 2002, 2006). For these reasons, and because of the widespread, but highly variable, nature of global biomass burning activity, EO data are considered key to better characterizing the extent and influence of this phenomena and are amongst the key datasets capable of being used to test, constrain and improve models of global fire-climate-vegetation interactions. In recent years advances in using EO to better quantify and characterize biomass burning at scales from individual fire events to continental-scale fire episodes have come from the development of FRP measures from geostationary (and other) sensors in order to estimate fuel burned and emissions released (Roberts et al., 2005; Wooster et al., 2005), and (ii) new methods to estimate daily burnt area and severity (Roy et al., 2005, 2008). Furthermore, the lengthening data records from high quality instruments such as MODIS and the ATSR series of sensors are now capable of capturing the widely varying nature of fire activity and its response to variations in climate (van der Werf et al., 2010) making the validation and optimization of global-scale fire-climate vegetation models more feasible than was the case previously with the more limited EO data records.

In addition to these active fire and post-fire measures, the model-forcing data are now much improved in the EOS (post-2000) era, with remotely derived measures of LAI, soil and vegetation moisture and land surface temperature now routinely produced from optical, microwave and thermal infrared sensors. With improved processing of historical data and nearly seven years of EOS-era observations, it is now particularly timely to exploit these advances to further develop and test regional- and global-scale fire models. Whilst the long-term future of all such observations is not yet secured, coordinating bodies such as the GOFC-GOLD Fire Implementation Team are making particular efforts in this area, as well as coordinating products, protocols and validation efforts.

The NERC-funded FireMAFS (Fire Modelling and Forecasting System) project (2008-2010) focused on systematic evaluation of the SPITFIRE fire model (Wooster et al., 2010). The project used climate fields from monthly CRU TS 3.0[8] and daily ERA interim data[9] to drive LPJ-DGVM-SPITFIRE to predict fire activity, fire intensity and emissions from biomass burning in several case study regions notably southern Africa, northern Australia, Indonesia, Amazonia, Russia and Canada. The project utilized parameter calibration / optimization techniques to test and improve the fire model. However, poor prediction of vegetation cover and biomass by LPJ-DGVM in some regions challenged this work. A solution was found to circumvent these shortcomings in the LPJ-DGVM by using MODIS data on vegetation cover to help initialize and constrain the vegetation model, which resulted in improved predicted fuel dynamics and litter moisture from model. This constraint exercise further permitted an improved calibration of parameters in SPITFIRE (based on Markov Chain Monte Carlo (MCMC) techniques and using MODIS burnt area data). In turn, this calibration exercise led to an improved prediction of burnt area by SPITFIRE (Gomez-Dans et al., in review).

Future Priorities for Model Improvement from an Earth System Perspective

The need for process-based fire-vegetation models to assess future impacts of climate change and land cover/land use change on fire activity and emissions from biomass burning is clear. We should not only be striving to improve the accuracy of current models but also increase their bio-physical realism. Growing attention is being given to positive feedbacks in the

8 http://badc.nerc.ac.uk/data/cru/
9 http://www.ecmwf.int/research/era/do/get/era-interim

earth system because of their potential to accelerate the effects of CO_2-induced changes to global and regional climates (Denham et al., 2007). A good example is the burning of forests in Amazonia to clear for agriculture, which is likely to continue into the future. The consequences of these impacts will cause global CO_2 to rise and regional rainfall to decrease, which in turn, could lead to high temperatures and lower humidity- both of which are conducive to even more fire (Cochrane, 2003; 2009). In parallel, the strong coupling between drought and fire activity / deforestation in Indonesia points towards a positive climate-carbon feedback since climate change is thought to enhance drought conditions here in the future (Li et al., 2007), increasing future CO_2 and CH_4 levels (van der Werf et al., 2008). Potential natural vegetation may then adapt to a drier and more seasonal climate, implying that ecosystems developing towards a new climate-vegetation state will become more fire prone, possibly fire adapted, and characterized by a carbon storage potential lower than the rainforest ecosystems they replace.

To study such feedbacks and predict their consequences, increased effort should be directed at implementing and running fire-vegetation models within fully coupled earth system models (containing in one form or another: a land surface model, an atmospheric chemistry model, a global circulation model (GCM), a bio-physical model of the ocean and ice). Figure 14.3 illustrates the importance of fire is in terms of earth system functioning, and the broad range of complex processes involved.

However, earth system modeling is still in its infancy, and the range of fire feedbacks described in Figure 3, to the best of our knowledge, have never been previously analyzed as part of an earth system model. One example of an earth system model project in which fire features prominently is the EMAC-LPJ-GUESS-SPITFIRE project, started in mid-2011 and scheduled for completion in 2014. This project involves the Max Planck Institute for Chemistry in Mainz, the Biodiversity and Climate Research Centre (BiK-F) and University of Mainz. The main aim of this project is investigate how emissions from wildfires and vegetation affect the carbon cycle, reactive gases production, and aerosol production; and how these effects interact with atmospheric chemistry and climate. The project combines existing coupled climate-atmospheric chemistry-aerosols model (EMAC) (Joeckel et al., 2006, 2008, 2010; Tost et al., 2007)[10] with state-of-the-art process-based models of i) vegetation/ forest dynamics (LPJ-GUESS) (Smith et al., 2001, 2011; Hickler et al., 2006, 2008)[11]; and ii) fire disturbances and emissions of trace gases and aerosols from wildfires (SPITFIRE) (Thonicke et al., 2010).

To quantify and predict the range of potentially important feedbacks shown in Figure 14.3, we believe the following processes/components need to be implemented in future coupled fire-vegetation models set within an earth system model. This is not an exhaustive list but rather a list of key areas in which improvements to the modeling should focus. The key areas identified are based on our collective knowledge of working with EO fire data,

10 http://www.messy-interface.org
11 http://www.nateko.lu.se/lpj-guess/lpj_guess_main.html

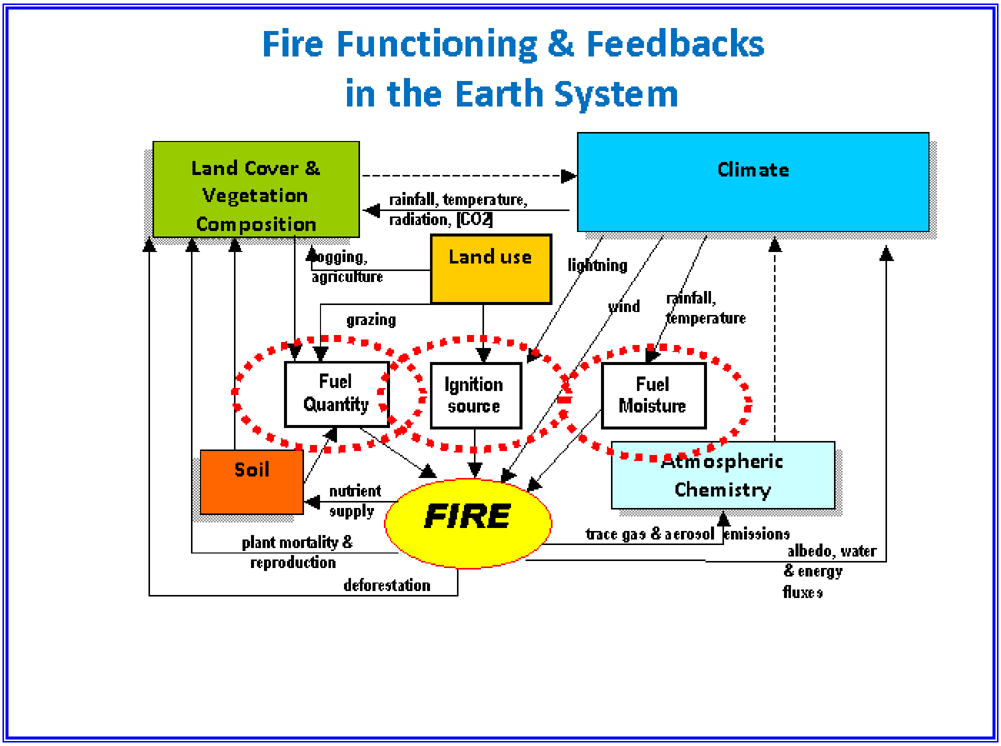

Figure 14.3. Fire functioning and feedbacks in the earth system, illustrating the three fundamental requisites for fire to occur: i) a sufficient amount of fuel, ii) sufficiently dry enough fuel; and iii) an ignition source.

process-based fire models, process-based vegetation models and earth system models. The principles discussed should generally apply to other modeling systems.

One, simulation of anthropogenic ignitions should take better account of the demographic and socio-economic factors driving them. Close to 100% of all wildfire in Africa are caused by humans (Saarnak, 2001), and a similar situation exists in respect of wildfires in the deforested areas of the tropics (van der Werf et al., 2008), Russia (Mollicone et al., 2006) and elsewhere. Currently the number of human-caused ignitions in SPITFIRE is simulated as a simple non-linear function of population density (Thonicke et al., 2010). The shape of this curve may be different for each gridcell, and is controlled by a single parameter derived from observed fire activity data (as opposed to burnt area data), and the observed length of the fire season. In future, however, ignitions forecasting should move towards a more explicit account of factors affecting ignitions – both proximate (e.g. land use, distance from secondary roads, population centres, logging coups (Cochrane et al., 1999; Chuvieco et al., 2008; Cardoso et al., 2009), and ultimate (e.g. agricultural and timber commodity prices) (Hooijer et al., 2006; Morton et al., 2006; Arima et al., 2007). One recent advance in this direction is the statistical analysis of Archibald et al. (2008). Although, this and similar analyses work at a different scale than typical DGVMs, and thus their results are difficult to directly incorporate into DGVMs. Another disadvantage is that statistical analyses often use land use parameter which are not available in projections for future climate scenarios which in turn further limits their applicability. Recently, Pfeiffer et al. (2013) describe a new representation in SPITFIRE for simulating anthropogenic biomass burning under preindustrial conditions that distinguishes the different relationships between humans and fire among hunter-gatherers, pastoralists, and farmers. While this new work resulted in improved fire simulations versus the original SPITFIRE model, it is largely empirical-based. Capturing the immense diversity of human–fire interactions at different spatio-temporal scales as part of future process-based models remains a major challenge.

Two, simulation of lightning-caused ignitions should always take into account that lightning flash frequencies are highly dependent on climate conditions. It is well known that lightning from dry thunderstorms can be a significant cause of fires in the tropical savannas during the dry-wet season transition (Williams et al., 2002) and in several other regions, notably western USA (Marlon et al., 2009), Russia (Suhkinin et al., 2004) and Canada (Fauria and Johnson, 2006). Further, climate model simulations suggest that lightning strike activity could, under certain conditions, become more prevalent in certain regions (Flannigan et al., 2005). Allen and Pickering (2002) reported a close relationship between flash rate and upward convective mass flux (MFLUX), and that MFLUX-based flash rates are most realistic compared with other indices of convective activity. Tost et al. (2007) assessed several combinations of state-of-the-art convection and lightning parameterizations used in simulations with the global atmospheric chemistry general circulation model ECHAM5/MESSy, against lightning observations. They concluded that a scheme based on cloud top height (CTH), which is related to convection, generally yielded more reliable results. Pfeiffer et al. (2013) implemented a new lightning-caused ignitions algorithm in SPITFIRE by scaling observed mean lightning flash rates (after Christian et al., 2003) with monthly anomalies of convective available potential energy (CAPE). This resulted in improved simulations natural fire occurrence compared with the original SPITFIRE. These studies indicate that simulating lightning flash rates as a function of convection-related variables is essential.

Three, landscape heterogeneity affects fire spread. A vast and growing body of remotely sensed data highlights the large-scale deforestation and fragmentation of natural forests that is occurring from the tropics to the boreal zone (Shvidenko et al., 2005). Further, the alarming prognosis is that this is likely to worsen in future as demand for agricultural and timber resources increases (Shvidenko et al., 2005). We know that as forest fragmentation changes, fire rate of spread and thus the amount of area burnt and emitted to the atmosphere is also likely to change (Siegert et al., 2001; Cochrane et al., 1999, 2002, 2003). Forest fragmentation can act as an impedance to fire spread, effectively reducing rate of spread. On the other hand, logging and fires in areas not usually subject to fires can create conditions that encourage future fires because of incursions by pyrophytic grass and woody shrubs which, in turn, lead to higher fine fuel loads and drier fuels surrounding the forest. Logging is also the first stage of land degradation from rain forest via a slash and burn culture to open areas with low productivity. Forest fragmentation also reduces the perimeter-to-area ratios of forest remnants further exposing them to fires from agricultural lands. Landscape fragmentation metrics derived from higher spatial resolution satellite data could be used to test how these affect rate of fire spread gained from MODIS or similar EO products. However, the quantification of these potential effects within a fire modeling framework remains a very complex and hitherto unexplored research question.

Four, previous fire modeling studies (either process- or inventory-based) have assumed constant emission factors (EFs) when simulating emissions of trace gases and aerosols from biomass burning (e.g. van der Werf et al., 2010; Thonicke et al., 2010). However, wildfires are characterized by two main forms of combustion– flaming and smoldering combustion; which implies that variable EFs should be used. It is the relative mix of these two types of combustion that generate the mix of species emitted from biomass burning. Flaming combustion or oxidation-type combustion reactions (e.g. production of CO_2, NOx) proceed at a faster rate when the fuel is dry and has a large surface-area-to-volume (SAV) ratio. The converse holds for smoldering combustion or reduction-type reactions (CO, CH_4 etc). A good example is the tropical savannas in which early dry season burns produce a higher CO/CO_2 ratio than those during the late dry season. If we are to realistically model trace gas and aerosol emissions from biomass burning, this problem needs to be resolved. Building on the methodology of Andreae and Merlet (2001), Korontzi (2005), van der Werf et al. (2010) and others, and recognizing that finer dry fuels burn more efficiently than coarser wetter fuels, first steps have been made towards to fixing this problem in SPITFIRE (Spessa et al., in progress) and in the GFED (van der Werf et al., in progress).

Five, forest crown fires are an important phenomenon in many regions in terms of its impact on tree mortality, and emissions of trace gases to the upper troposphere (Pyne et al., 1996). Further, pyro-cumulonimbus clouds associated with thunderstorms in the area of a severe forest fire can have its vertical lift enhanced to boost smoke, soot and other particulate matter as high as the lower stratosphere (Rosenfeld et al., 2007). While none of the current fire-vegetation models simulates active crown fires, LPJ-GUESS and ED unlike LPJ and other 'traditional' DGVMs are able to track heights of different patches of forests caused by different disturbance histories. Thus, in principle, LPJ-GUESS and ED would not need to be radically altered to account for crown fires. Nonetheless, crown fires are a complex phenomena, dependent on non steady-state weather conditions which are poorly resolved at the daily time step resolutions we normally run coupled fire-vegetation models in off-line mode, and which are often themselves caused by the large convective forces generated by such fires (van Wagner, 1977; Pyne et al., 1996; Finney, 1998; Scott and Reinhardt, 2001; Butler et al., 2004). Like other GCMs, HadGAM1 simulates weather on a half hourly time step- a scale that is more relevant to crown fires initiation and spread, but its resolution like most of its contemporaries is very low (~150kms). While this is likely to improve to 90 km with the next generation of models, fine scale weather changes remain a significant challenge to simulating crown fires as part of earth system models. Recent efforts to parameterize GCMs to better account for wind sheer and convective buoyancy fluxes at finer scales as part of extreme weather prediction (e.g. Shaffery et al., 2008) offers hope for the immediate future, however.

A coupled atmosphere-wildland fire simulation model has been developed in the last decade by the National Centre for Atmospheric Research (NCAR) to represent the complex interactions between fires and local winds (Clark and Hall, 1996; Clark et al., 2004; Coen, 2005). This coupled atmosphere-fire model is composed of a wildfire simulation model, based on the Rothermel fire rate of spread equation (Rothermel, 1972) driven by prescribed fuel load and structure, that has been embedded within the Clark-Hall atmospheric numerical model. The atmosphere and fire are fully coupled in that evolving modeled atmospheric information is used to drive the propagation of the fire line, and the sensible and latent heat from the fire model is released into the modeled atmosphere, greatly changing the atmospheric motions, creating strong convective updrafts, convergence near the surface, and strong near surface winds that, in turn, determine the spread rate and direction of the fire (Coen, 2005). Current work is focusing on embedding the atmosphere-fire model within the Weather Research and Forecasting Model (WRF), which is used for both research and operational weather prediction (Michalakes et al., 2000), by parameterizing weather processes at 1km resolution or less.

Six, none of the fire-vegetation models currently considers peat fires. This gap needs to be redressed because peat fires are emerging as a global threat with significant economic, social and ecological impacts. About 60% of the world's wetlands are peat, and the distribution of peats ranges from the tropics to the boreal zone (Flannigan and de Groot, 2009). Peat has high carbon content and can burn under low moisture conditions. Once ignited by the presence of a heat source (e.g. a wildfire penetrating the subsurface), it smolders. These smoldering fires can burn undetected for very long periods of time (months, years) propagating slowly through the underground peat layer.

Recent burning of peat bogs in Indonesia, with their large and deep growths containing more than 50-60 Pg C (Jaenicke et al., 2008), has contributed to increases in global CO_2 levels (Page et al., 2002; van der Werf et al., 2008, 2010; Spessa et al. 2010; cf. Page et al. (this volume, Chapter 7). Currently, peatland forests in Southeast Asia are at serious risk from unsustainable land use practices (notably drainage for agriculture and plantations, and wild fires); and could be completely degraded or destroyed over the next century (Hooijer et al., 2006). During the El Niño-induced drought of 1997, it is estimated that peat and forest fires released between 0.81 and 2.57 Pg C. This is equivalent to 13-40 percent of the average annual amount released by global burning of fossil fuels during the 1990s, and greater than the carbon uptake of the world's biosphere (Page et al., 2002). Recent work by van der Werf et al. (2008) show that other El Niño events during the past decade have also caused large spikes in emissions from peat fires in south east Asia. Spessa et al. (2010) highlight the complex interplay between El Niño-driven drought and deforestation in driving fire activity and emissions in the region, which have important implications for predicting climate change impacts there. Several global and regional climate modeling studies have reported that equatorial SE Asia, including Borneo, will experience reduced rainfall in future decades (e.g. Li et al., 2007). At the same time, demands for establishing pulp paper and palm oil plantations to replace native rainforests, especially on peat lands where tenure conflicts among land owners tend to be minimal, is forecast to increase. These joint scenarios imply even more fires and emissions in future.

Between 70-100 Pg of carbon are estimated to stored in circumpolar boreal peatlands (Flannigan and de Groot, 2009). Recent climate change projections concerning high latitude regions forecast increased melting of permafrost (Solomon et al., 2007) and decreased soil moisture (Dai, 2010). Although climate change projections for the high latitudes are subject to high levels of uncertainty, these projections suggest that peat fires in the boreal zone will become more common, and the associated emissions from such fires will increase (Flannigan and de Groot, 2009).

A wetlands/peat module would be a necessary precursor to implementing boreal and tropical peat fires in GUESS-SPITFIRE. Work has recently commenced on implementing wetlands in LPJ-GUESS, including new Plant Functional Types (PFTs) and processes pertaining specifically to their biogeochemistry and hydrology, based on studies by Woesten et al. (2008) and Wania et al. (2009a, b; 2010) (Ben Smith, pers. comm.). While accounting for depth of peat burning under different soil moisture conditions is not a straightforward task; previous work offers a guide. Frandsen (1987) calculated burn depth as a function of moisture, inorganic content and organic bulk density for a sample of organic soils in Canada. Ballhorn and Siegert (2009) have done similar work for the peatlands of Kalimantan and Sumatra. In both works, moisture content seems to be the main driving variable controlling burn depth. Since moisture content increases with increasing depth from surface, one could theoretically use SPITFIRE to simulate above ground spread of fire, and then, if a surface fire is simulated, use the moisture content of the organic soil at successive levels to determine depth of burn, and thus the amount of peat combusted. However, the challenge remains as to how best to simulate peat fires at the coarse resolution of an earth system model.

Conclusions

- Fires have been known to be a major source of trace gases and aerosols, for some species rivaling the amounts emitted by fossil fuel combustion.
- Improved satellite data and sophisticated biogeochemical modeling enables emissions assessments on a global scale with fine spatial and temporal resolution. Emissions estimates are still comparable to those based on older inventory-based techniques, but uncertainties remain large.
- Fires increase during El Niño periods because parts of the tropics where humans use fire as a tool for deforestation experience drought conditions. These spikes contribute to the inter-annual variability of CO_2 and CH_4 observed in the atmosphere.

- There is no alternative to the use of process-based coupled fire-vegetation models for the assessment of future fire regimes and emissions under changing climate, vegetation and/or land use, and the assessment of fire management strategies. Though their development is still at an early stage, this modeling approach is the only one that can be used in a predictive rather than a descriptive way.
- Recently developed dynamic fire-vegetation models are capable of simulating the extent of wildfires as well as their emissions of CO_2 and other greenhouse gases for ambient as well as for projected climatic conditions.
- The performance of fire-vegetation models however needs to be strongly improved and validated by field studies investigating the processes leading to emissions as well as by remotely sensed approaches linking recent climate with vegetation, fires and burned areas as well as by socio-geographic studies.
- Wildfires in their effect as well as in their origin can have a high socio-geographic component (e.g. in Africa, deforested areas of the tropics and Western Russia). On the other hand, lightning-caused fires can also be significant (e.g. in western USA, Canada, northern boreal Eurasia and northern Australia), and as such, also need to be taken into account by fire-vegetation models where appropriate.
- Further improvements to fire-vegetation models should not only focus on ignitions, but also: the way fire spreads through a heterogeneous landscape; fire-induced tree mortality and fire-induced ecological succession; crown fires; bio-climatically sensitive emission factors; and the mounting problem of peat fires in Indonesia and the boreal zone.

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